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Geochemistry and provenance of stream sediments of the Ganga River and its major tributaries in the Himalayan region, India

Pramod Singh *

Department of Earth Sciences, School of Physical, Chemical and Applied Sciences, Pondicherry University, Pondicherry-605014, India

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ABSTRACT

Major, trace and REE compositions of sediments from the upper Ganga River and its tributaries in the Himalaya have been examined to study the weathering in the Himalayan catchment region and to determine the dominant source rocks to the sediments in the Plains. The Ganga River rises in the Higher Himalaya from the Higher Himalayan Crystalline Series (HHCS) bedrocks and traverses over the Lesser Himalayan Series (LHS) and the Himalayan foreland basin (Siwaliks) rocks before entering into the Gangetic Plains. The major element compositions of sediments, reflected in their low CIA values (45.0–54.7), indicate that silicate weathering has not been an important process in the Himalayan catchment region of the Ganga River. Along the entire traverse, from the HHCS through LHS and the Siwaliks, the sediments from the tributaries and the mainstream Ganga River show higher Na_2O, K_2O, CaO and silica. This, and the higher ratios of La/Sc, Th/Sc and lower ratios of Co/Th, suggest that the source rocks are felsic. The fractionated REE patterns and the significant negative Eu anomalies ($Eu/Eu^* = 0.27–0.53$) indicate highly differentiated source. Moreover, the comparison of the sediments with different source rock lithologies from the HHCS and the LHS for their major elements clearly suggests that the HHCS rocks were the dominant source. Further, comparison of their UCC (upper continental crust) normalized REE patterns suggests that, among the various HHCS rocks, the metasediments (para-gneiss and schist) and Cambro-Ordovician granites have formed the major source rocks. The Bhagirathi and Alaknanda River sediments are dominantly derived from metasediments and those in the Mandakini River from Cambro-Ordovician granites. The resulting composition of the sediments of the Ganga River is due to the mixing of sediments supplied by these tributaries after their confluence at Devprayag. No further change in major, trace and rare earth element compositions of the sediments of the Ganga River after Devprayag up to its exit point to the Plains at Haridwar, suggests little contribution of the Lesser Himalayan and Siwalik rocks to the Ganga River sediments.

1. Introduction

Chemical weathering of rocks is a major geological process that affects the atmospheric CO_2 concentration, and hence affects global climate (Berner, 1992, 1995; Dupré et al., 2003). At the same time it also affects the nature of sediments produced, and the solute chemistry of rivers, which ultimately controls the ocean water chemistry (Stallard and Edmond, 1983, 1987; Bluth and Kump, 1994; Galy and France-Lanord, 2001). Even though the bedrock is transformed into soil and ultimately into sediments by the combined effects of chemical, biological and physical weathering processes, in response to climate and topography, the original signature of the source still remains preserved in the sediments. The distribution of some trace elements such as Sc, Th, Zr, Cr, Ni Co and REEs, which generally remain immobile during several processes of sediment production, is a useful indicator of source region composition. Thus, sediment geochemistry helps us to decipher the geological evolution of its source region. The sediment chemistry also reflects the nature of weathering at the source, which, in turn, is controlled by climatic and tectonic factors, although there is a strong debate on their dominant influence (Raymo et al., 1988; Drever and Zobrist, 1992; Edmond, 1992; Raymo and Ruddiman, 1992; Derry and France-Lanord, 1996). Thus, in addition to deducing provenance the chemistry of sediments is also a useful indicator of climate and tectonics of the catchment region.

The Ganga River, which drains complex rock types in the Himalaya and passes through diverse climatic and physiographic regions, contributes significantly to the global sediment budget and water discharge to the ocean. The nature of weathering in the Himalaya and its contribution to the solute load are believed to have significant influence over the global climate and ocean water chemistry, particularly after its tectonic upliftment due to the convergence of the Indian and Tibetan plates during the Cenozoic. Thus, it provides immense opportunity to understand the effect of relief, tectonics and

* Tel.: +91 413 2654489.
E-mail address: pramods@yahoo.com.

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climate on the nature of the derivative sediments, and the rate of erosion. The above facts attracted the attention of several workers, who generally relate the chemical and isotopic signature of the solute load of the Ganga River to the nature of chemical weathering in the Himalayan region, and to the change in the ocean water chemistry, particularly during the Cenozoic (Palmer and Edmond, 1989; Vieizer, 1989; Palmer and Edmond, 1992). Raymo and Ruddiman (1992) and Richter et al. (1992) have suggested that the tectonic uplift due to the convergence in the Himalayan region during the Cenozoic could have resulted in increased silicate weathering and elevated $^{87}Sr/^{86}Sr$ ratio of the river water and the ocean since 40 Ma. Since then, the tectonic uplift is also believed to have exerted a strong influence on the chemical budget of some other elements in ocean waters at the global scale (Krishnaswami et al., 1992; Richter et al., 1992; Edmond, 1992; Palmer and Edmond, 1992; Derry and France-Lanord, 1996; Galy et al., 1999). Raymo and Ruddiman (1992) further proposed the theory of global cooling during the Cenozoic as a result of the Himalayan uplift. Their major assumption was that the uplift could have caused enhanced erosion and chemical weathering of the sediments derived from the Himalaya, resulting in an increased rate of CO_2 drawdown (a greenhouse gas), and consequent climate cooling. Since then, the above theory for global cooling has been debated by many researchers. Krishnaswami et al. (1992), Richter et al. (1992), Krishnaswami et al. (1999), Bickle et al. (2003) and Edmond (1992) in their studies have inferred silicate weathering as the dominant source for high $^{87}Sr/^{86}Sr$, whereas Palmer and Edmond (1992), Quade et al. (1997), Harris et al. (1998) and Jacobson et al. (2002) have proposed carbonate weathering as the reason for higher $^{87}Sr/^{86}Sr$. If carbonate weathering had been the source for higher $^{87}Sr/^{86}Sr$ ratio of sea water since the Himalayan uplift, it cannot account for the CO_2 drawdown due to weathering as proposed by Raymo and Ruddiman (1992). Jacobson and Blum (2003) have suggested that the Himalayan and other mountain uplift promote physical weathering by means of glaciation, and not carbon consuming chemical weathering. The debate on the cause of climate change during the Cenozoic calls for further work on the weathering in the Himalaya.

The above inferences on weathering and source of solution input to the Himalayan river water and ultimately to the ocean rely mainly on the chemistry of solute load, and selected carbonate and silicate fractions of the bed load sediments from the Himalayan region, or from the mouth of the river in Bangladesh, or studies carried on few sections from Siwaliks. But none of these studies includes full chemical signature of the detrital sediments. According to an estimate made by Galy and France-Lanord (2001), the total erosion flux from the Himalaya, is double that of the estimate made on the basis of suspended load fluxes in Bangladesh. This implies that the sediments derived by the Himalayan Rivers have variable residence time on land. It is noteworthy that the Himalayan Rivers in general and the Ganga in particular, travel a long distance in the hilly tract and in the Plains before meeting the sea. It also passes through diverse climatic zones, starting from frigid in the upper reaches to warm and humid in the Plains region. Due to higher residence time on land and climatic variation along its tract between hill and the ocean, the sediments may possibly be subjected to changes in addition to those brought by the weathering at their source. These en route changes in sediments may significantly change the solute chemistry of the river waters. Consequently inferences made on the nature of weathering and source of solution input to the ocean, based only on studies of the solute load of the rivers from the Himalayan catchment region, may at times be ambiguous. It is therefore imperative to systematically study the geochemistry of the sediments of these large Himalayan Rivers for the entire stretch from hills to the Plains, to reinterpret the source of the chemical fluxes finally reaching the ocean. In the present study major, trace and rare earth element geochemistry of the sediments collected from the Ganga River and its tributaries, while they pass through different lithological units of the Himalaya, i.e. HHCS, LHS and the Foreland basin deposits (Siwaliks) (Fig. 1), have been examined to evaluate the nature of weathering, sources of sediments in different tributaries, results of mixing of different tributaries and the final output to the river in the Plains. In another study (Singh, 2009) I have reported the chemistry of sediments collected from the different parts of the Ganga Plain, and tried to evaluate the chemical changes brought during their residence in the Plain region as a consequence of different climatic conditions.

2. Geology of the study area

The Himalayan orogeny was a result of Late Cretaceous and early Tertiary (70–40 Ma) collision of the Indian plate with the Eurasian plate. The subduction of Indian plate followed by its collision resulted into series of northward dipping thrust faults, which divided the Himalaya into three tectonic units (Fig. 1) from north to south namely, Higher Himalayan Crystalline Series (HHCS), Lesser Himalayan Series (LHS) and the Siwaliks exposed at different elevations decreasing from north to south. To the North the HHCS is separated from Tethyan strata, which are also known as the Tethyan sedimentary series (TSS), by the Indus–Tsangpo suture zone (ITSZ). The HHCS is made up of high grade late Proterozoic middle and deep crustal metasedimentary rocks (gneisses, schist, quartzites, and metabasics) and biotite ± muscovite granites of Cambro-Ordovician age, with limited carbonate and calcsilicate rocks (Gannser, 1964; Valdiya, 1995). These rocks were subsequently metamorphosed, and later deformed during 500 Ma and Early Miocene between 35 and 20 Ma (Searle et al., 1999). The grade of metamorphism in this series changes from high grade kyanite/sillimanite in the north, to lower-amphibolite and biotite grade in the south. In the north these metasediments, in the Garhwal Himalaya, are intruded by tourmaline + biotite + muscovite ± garnet bearing leucogranites of Miocene/Pliocene age (Searle et al., 1999) that forms high rising plutons (relief > 2000 m) together known as Badrinath–Gangotri granite. The HHCS has the steepest relief, with an average elevation of 4700 m and a range from 1200 m to 7800 m. The southern face of the HHCS is a scarp, 3000–4000 m in elevation (Valdiya, 1980). To the south, the HHCS is separated from another unit, the LHS, by Main Crystalline Thrust/Zone (MCT). The LHS has much lower relief, and an average elevation of 2500 m. The LHS is comprised of Precambrian–Paleozoic pre-Himalayan rocks, metamorphosed to lower grade schist, phyllites, quartzite, calc silicate and variably impure limestone and dolomite (Valdiya, 1995; Johnson and Oliver, 1990). The LHS to its south is delimited by Main Boundary Thrust (MBT), which also forms the northern boundary of Ganges Foreland Basin known as Siwaliks. Siwaliks is comprised of unmetamorphosed sediments deposited in response to the collision, which resulted in rise and erosion of Himalaya.

The Ganga River system is comprised of the Ganga trunk river and its tributaries, the major one being the Bhagirathi, Alaknanda and Mandakini (Fig. 1). The headwater of the Bhagirathi River rises at an altitude of > 4000 m, and Alaknanda River rises at an altitude of ~3500 m from the glaciated valleys of HHCS. Both these tributaries, in this part flow over high grade metasediments, and are surrounded by precipitous cliffs of leucogranites of Mio-Pliocene age that forms high peaks (> 6000 m) with high relief in this part. These two tributaries, then cross various HHCS rocks and enter into the region of LHS rocks before their confluence at Devprayag. These tributaries, in their initial course over HHCS rocks, have very high gradient, e.g. Bhagirathi River in its traverse up to Harsil, descends by > 30 m/km, and Alaknanda River in its initial course up to Joshimath, descends by 30 m/km. Thereafter, gradient of Bhagirathi River between Harsil and Devprayag, in a space of ~200 km, reduces to 10 m/km. In case of Alaknanda River, the gradient further reduces to 3 to 4 m/km between Joshimath and Devprayag. In the HHCS region, after descending from the leucogranite zone, the Bhagirathi River flows over kyanite–